Arizona Geological Society Digest 22
2008

Overview of the Late Triassic Galore Creek copper-gold-silver porphyry system, northwestern British Columbia, Canada

Danette L. Schwab, Scott Petsel, Bruce R. Otto, Stuart K. Morris, Erin E. Workman
NovaGold Resources, Vancouver, British Columbia, Canada

Richard M. Tosdal
Mineral Deposits Research Unit, University of British Columbia, Vancouver, British Columbia, Canada

ABSTRACT

The Galore Creek alkalic Cu-Au-Ag porphyry is located within the Stikine Arch at the western margin of the Intermontane Belt in northwestern British Columbia, Canada. It represents a unique mineralized center associated with a silica undersaturated intrusive complex emplaced into the Upper Triassic volcaniclastic strata of the Stuhini Group. At least twelve Cu-Au mineralized zones are associated with the intrusive complex. The supracrustal host rocks were deposited in a deep marine basin isolated from a continental sediment source. Multiple syenite intrusions form a complex of dikes and stocks that intrude the volcanic and volcaniclastic rocks and are associated with the known Cu-Au mineralized centers. Alteration spatially distributed around the intrusive complex suggests that the intrusives played a causative role. In the Central Zone, the best documented mineralized center, a peripheral K-silicate assemblage of high bornite and high Cu-Au concentration surrounds a core of pervasive Ca-K-silicate alteration characterized by the presence of garnet, high Cu and lower Au concentrations. Hydrothermally cemented breccias, which locally contain Cu-Fe sulfides, occur along the margins of orthoclase syenite megaporphyry intrusions and may represent the last of at least two phases of porphyry-style mineralization documented at Galore Creek. Fluid inclusion and sulfur isotope data demonstrate that hydrothermal fluids associated with the deposits were saline, oxidized, and indicative of a magmatic source.

INTRODUCTION

Alkalic Cu-Au porphyry deposits occur in only a few metallogenic terranes, notably the Ordovician and early Silurian Lachlan Fold Belt in New South Wales, Australia (summarized by Cooke et al., 2007), and the Triassic and Jurassic marine volcanic arc of British Columbia, Canada (Barr et al., 1976; Lang et al., 1995a). In British Columbia (BC), the deposits are associated with silica-saturated and silica-undersaturated shallow-level igneous complexes (Lang et al., 1995b). These deposits, in addition to the calc-alkaline porphyry Cu-Mo deposits, have historically accounted for significant Cu production, such as from Copper Mountain, Afton-Ajax, and Mount Polley (Fig. 1) (Schroeter et al., 2004). The Galore Creek Cu-Au-Ag alkalic porphyry deposit is one of a suite of Late Triassic Cu-Au alkalic porphyries in BC. This deposit, hosted in the Stikine Terrane (Fig. 1), represents one of the largest undeveloped resources in BC. Since 2003, Galore Creek has been explored by NovaGold Resources Inc. (formerly SpectrumGold Inc.), and since mid-2007 as a joint venture with Teck Cominco Ltd. As of March 2007, measured and indicated resources total 928.4 million tonnes grading 0.5% Cu, 0.28 g/t Au and 4.7 g/t Ag.

e-mail: Schwab: danetteschwab@gmail.com; Petsel: scott.petsel@novagold.net; Otto: bruce.otto@novagold.net; Morris: stuart.morris@novagold.net; Workman: erin.workman@novagold.net; Tosdal: rtosdal@eos.ubc.ca

Schwab, D.L., Petsel, Scott, Otto, B.R., Morris, S.K., Workman, E.E., and Tosdal, R.M., 2008, Overview of the Late Triassic Galore Creek copper-gold-silver porphyry system, northwestern British Columbia, Canada, *in* Spencer, J.E., and Titley, S.R., eds., Ores and orogenesis: Circum-Pacific tectonics, geologic evolution, and ore deposits: Arizona Geological Society Digest 22, p. 471-484.

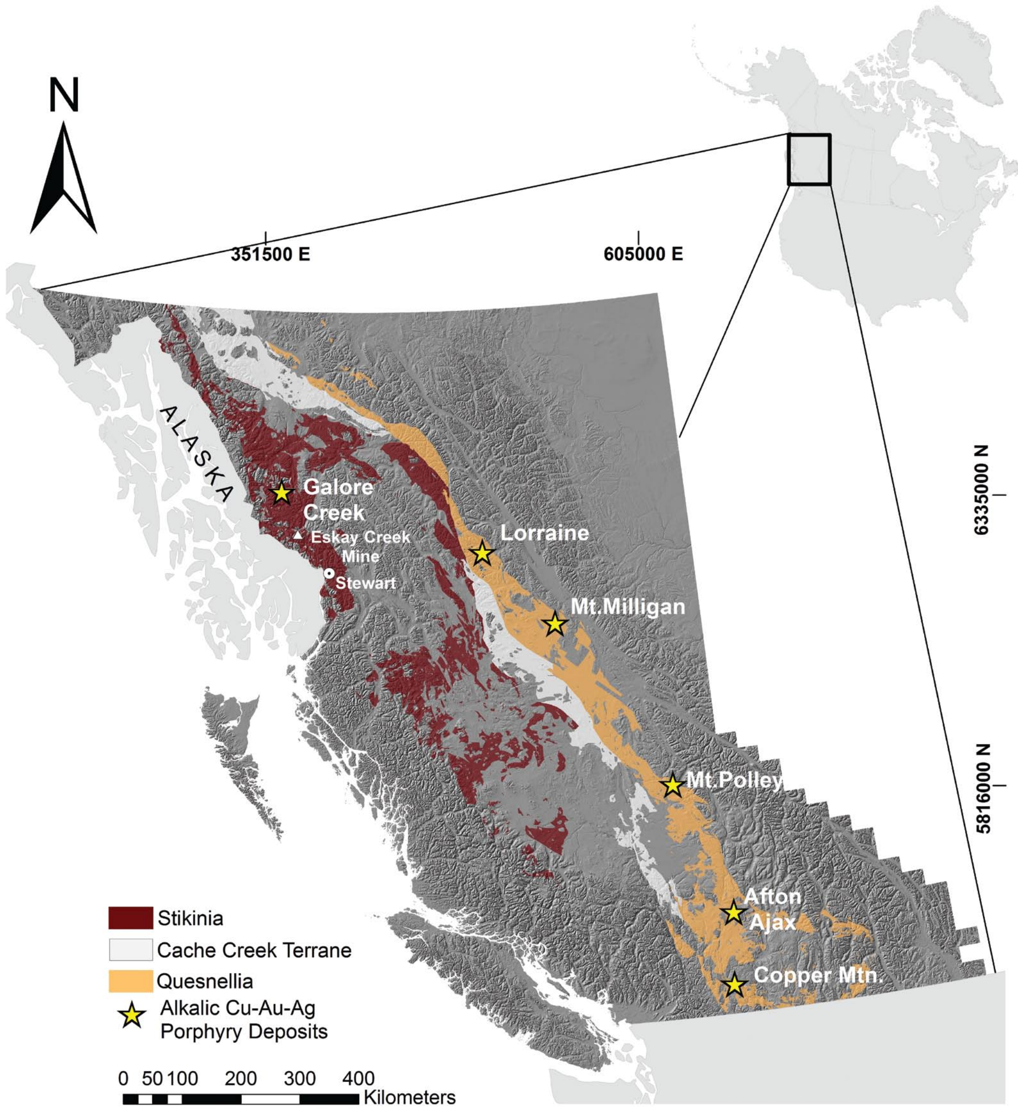

Figure 1. Distribution of Stikinia, Cache Creek and Quesnel terranes. Significant Cu-Au alkalic porphyry prospects are indicated by stars.

Located approximately 150 km northeast of Stewart, BC, and 75 km northwest of the Eskay Creek Au-Ag mine, the Galore Creek district was discovered in the 1950s and has been explored with varying degrees of intensity since then (Enns et al., 1995 and references therein). The Galore Creek property contains at least 12 mineralized occurrences of which the Central Zone is the largest and best delineated (Fig. 2). Other important zones include the Bountiful, Southwest, West Fork and Junction deposits (Fig. 2). Another mineralized center, the Copper Canyon Cu-Au-Ag alkalic porphyry deposit, is located 6 km east of Galore Creek (Fig. 3). The mineralized centers are associated with distinctive silica-undersaturated feldspathoidal syenite and monzonite porphyry that have intruded feldspathoidal felsic and augite-phyric basaltic volcaniclastic rocks and flows deposited in a marine setting (Panteleyev, 1976; Monger, 1977; Enns et al., 1995). The intrusions are considered to be some of the most silica-undersaturated rocks known to host a porphyry deposit (Lang et al., 1995a, b; Enns et al., 1995), suggesting that Galore Creek is an end member example of the alkalic porphyry Cu-Au class (Lang et al., 1995a).

In general, alkalic porphyry Cu-Au deposits have characteristics that distinguish them from the more common calc-alkaline porphyry Cu-Mo deposits. Included is the presence of characteristic calc-potassic alteration in the high-temperature cores of the deposits, abundant igneous and hydrothermal magnetite, absence of significant molybdenum, and near absence of phyllic, argillic and advanced argillic alteration assemblages (Lang et al., 1995a; Wilson et al., 2003). There is also a general paucity of quartz either in veins or as wall-rock replacement particularly in those deposits associated with silica undersaturated igneous complexes. In contrast, systems associated with silica-saturated igneous complexes may have significant quartz veins, such as those in the Cadia-Ridgeway deposits of New South Wales, Australia (Wilson et al., 2003; Cooke et al., 2007) or volumetrically minor quartz veins such as at Mount Milligan

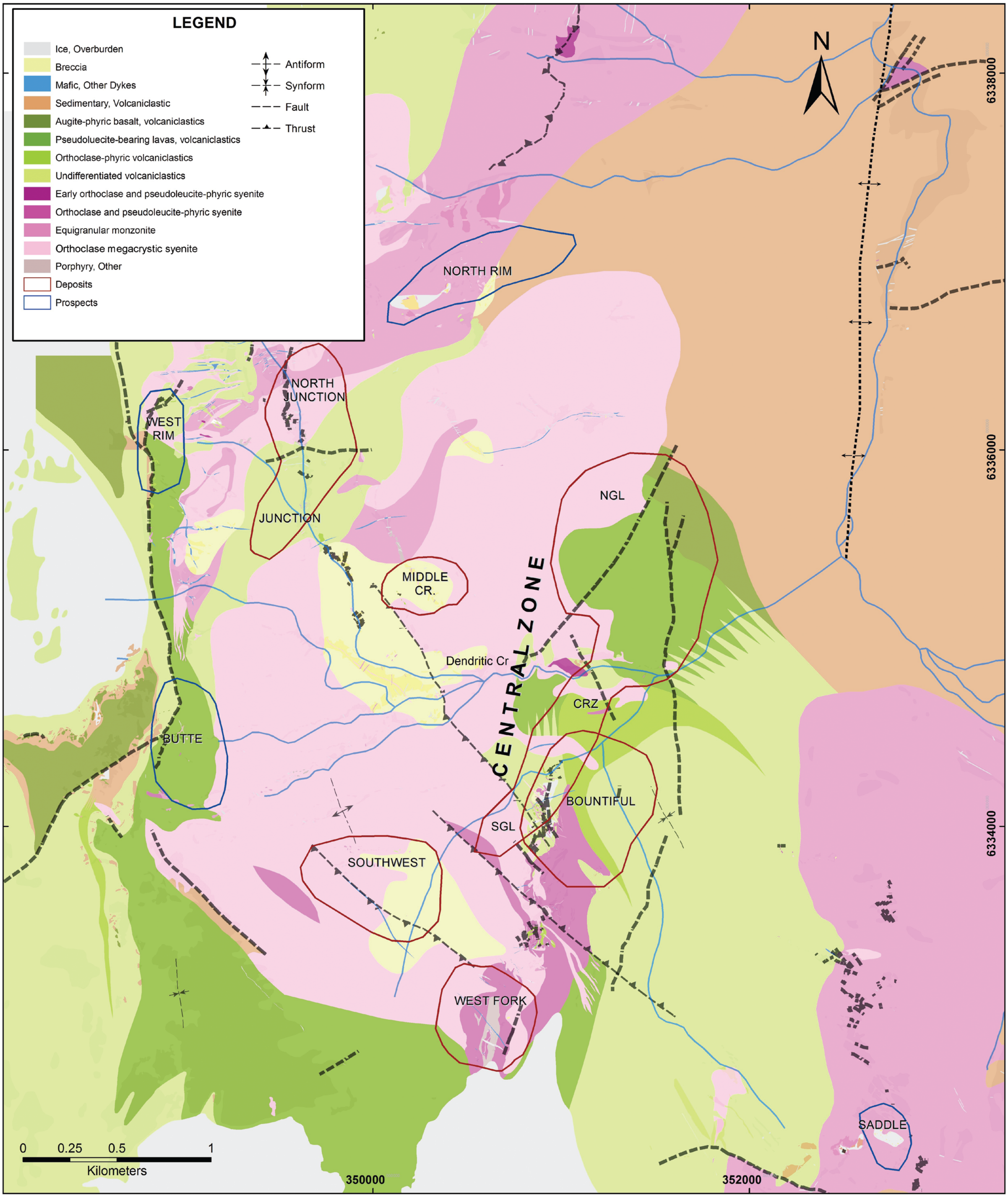

Figure 2. General geology of Galore Creek and location of mineralized zones. CRZ, Central Replacement Zone; NGL, North Gold Lens; SGL, South Gold Lens.

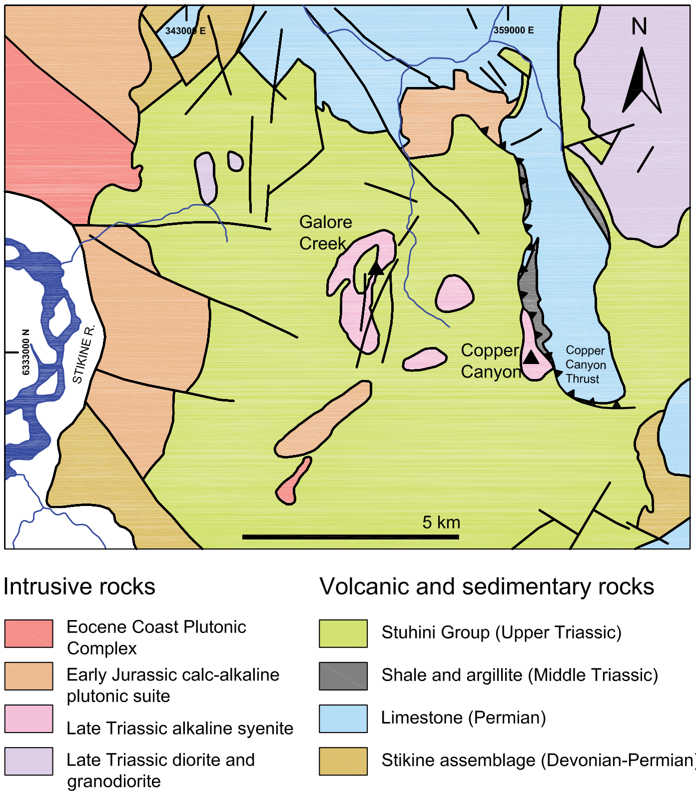

Figure 3. Regional geology of the Galore Creek area (after Logan and Koyanagi, 1994).

(Sketchley et al., 1995; Jago et al., 2007). The Galore Creek deposits are associated with shoshonitic volcanic and intrusive rocks that have several magmatic lineages (Enns et al., 1995). Igneous melanitic garnet has been noted in some of the alkalic plutons in BC, particularly in the more silica-undersaturated varieties such as Galore Creek (Lang et al., 1995c; Russell et al., 1999) and may be important in the recognition of alkalic porphyry deposits. Alkalic porphyry deposits tend to form clusters of small multiple intrusive centers, many of which are associated with intrusions a few hundred meters in diameter (Lang et al., 1995a; Lickford et al., 2003; Wilson et al., 2003). Galore Creek is characterized by these features, however as an end-member deposit, it is also unique in the abundance of hydrothermal garnet alteration and a large K-silicate alteration footprint (Enns et al.., 1995; Lang et al., 1995a). These characteristics and their bearing on the origin of the enigmatic deposits at Galore Creek are presented in this overview.

GEOLOGIC FRAMEWORK

The Galore Creek deposit lies within the Stikine Arch, a regional northeast-trending transcurrent structure of uncertain origin. The region is underlain by accreted Devonian to Early Jurassic marine volcanic island-arc rocks of the Stikine Terrane, also known as Stikinia (Fig. 1). East of Stikinia are Mississipian to Triassic rocks of the Cache Creek Terrane. Similarities in rock type and geologic history between Stikinia and Quesnellia, including the presence of the silica-undersaturated alkalic porphyry deposits, have led workers to believe that they are segments of the same Triassic arc (Wernicke and Klepacki, 1988; Nelson and Mihalynuk, 1993; Mihalynuk et al., 1994). The unusual juxtaposition of the oceanic Cache Creek Terrane situated between the arc terranes of Quesnellia and Stikinia (Fig. 1) has been attributed to oroclinal folding (Nelson and Mihalynuk,1993) or strike-slip faulting (Wernicke and Klepacki, 1988). The Stikinia-Quesnellia arc assemblages were accreted to the North American craton margin in the Middle Jurassic, between 180 and 170 Ma, (Travers, 1978; Mihalynuk et al. 2004) at which time marine arc magmatism ceased in the region (Plafker and Berg, 1994). Cretaceous and Eocene granitic rocks of the Coast Plutonic Complex intrude the Stikine Terrane to the west of Galore Creek (Fig. 3).

In the Galore Creek area, the basement to Stikinia is an amalgamation of Upper Paleozoic primitive island-arc assemblages composed of Carboniferous and Devonian calc-alkaline volcanic rocks interbedded with sedimentary rocks, and overlain by extensive Early Permian carbonate rocks (Logan and Koyanagi, 1994). A relatively thin succession of Lower and Middle Triassic carbonaceous sedimentary rocks overlies the Permian limestone. The Middle to Upper Triassic Stuhini Group unconformably overlies the Stikine assemblage (Fig. 3). Stuhini Group rocks are important hosts to the alkaline intrusive-related Cu-Au-Ag mineralization at Galore Creek and comprise a variety of flows, tuffaceous rocks, volcanic breccias and finer grained volcaniclastic rocks. Within the deposit area, the Stuhini Group consists of a lower subalkaline hornblende and plagioclase-phyric basaltic andesite, a medial subalkaline to alkaline augite-phyric basalt with accompanying sedimentary rocks, flow breccias and dikes, and an uppermost alkaline orthoclase and pseudoleucite-bearing shoshonitic basalt (Logan and Koyanagi, 1994; Enns et al., 1995). The rocks generally dip to the southwest in the deposit area.

Otto (2004, 2006) outlined transitions from subaerial and shallow water depositional environments in the Copper Canyon area deepening westward towards sub-wave base environments at Galore Creek (Fig. 4). Copper Canyon geology is dominated by pseudoleucite and orthoclase-phyric hypabyssal intrusions and aphyric and orthoclase porphyritic mafic alkalic lavas. An overlying eruptive sequence consists of pyroclastic rocks which contain lithic lapilli fragments. Accretionary lapilli within the pyroclastic package suggest subaerial deposition. Sedimentary rocks interpreted as lacustrine beds, fluvial sandstone and conglomerate indicate a shallow depositional environment. West of Copper Canyon, the volcaniclastic sedimentary rocks lack primary pyroclastic features. Several kilometers west, a dramatically thickened stratigraphic section contains abundant mud-matrix debris flows, interbedded pillowed mafic and alkaline lava flows, and thinly bedded turbidites. This data suggests that the transition between the dominantly subaerial and subaqueous facies occurred across generally northwesterly-trending fault structures that deepened the basin to the west.

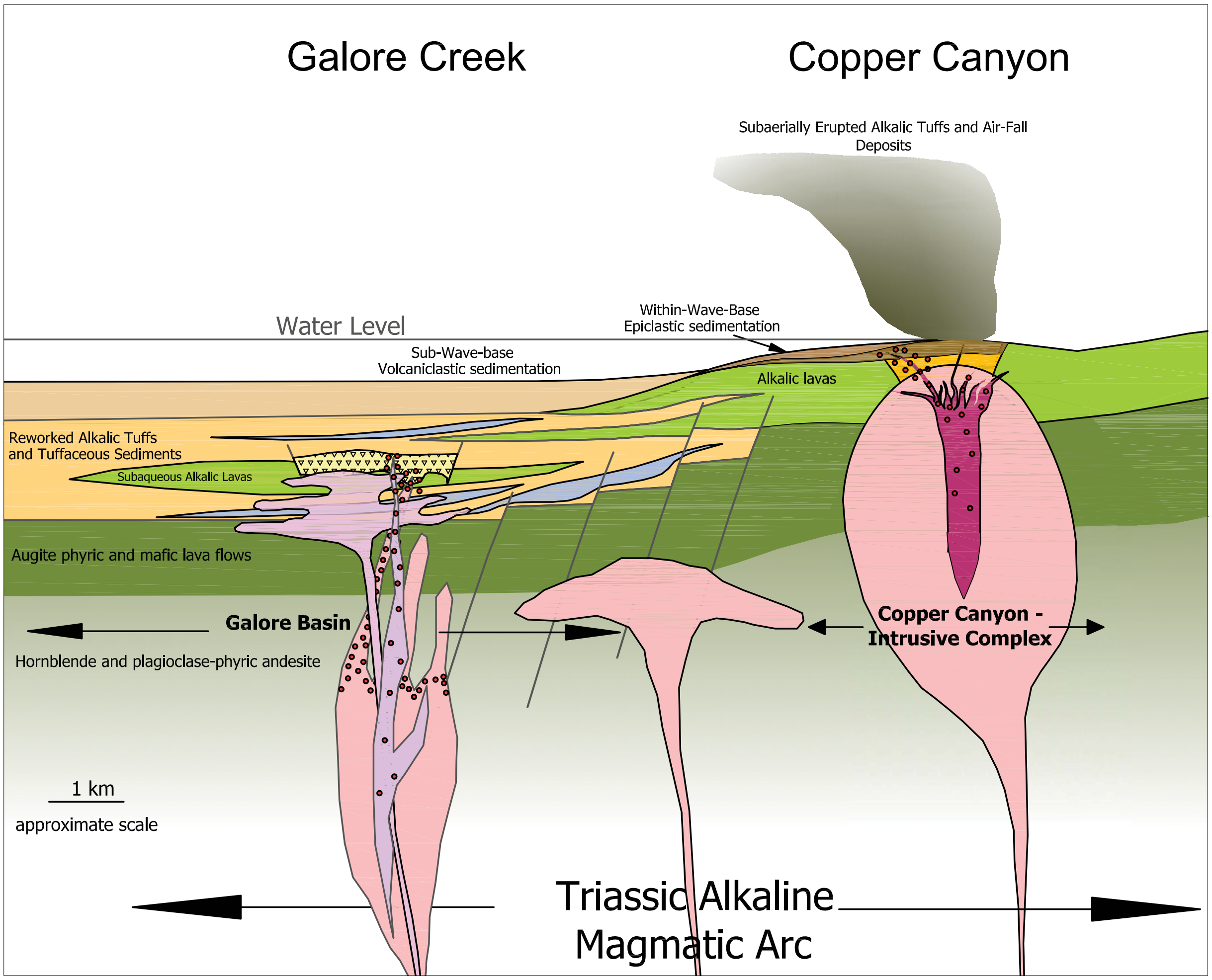

Figure 4. Schematic tectonostratigraphic cross section from Copper Canyon to Galore Creek depicting interpreted paleogeography of the host volcanic and volcaniclastic sequences.

Pre-, syn- and late-mineral syenitic and monzonitic intrusives of the Galore Creek Suite intrude the supracrustal package (Enns et al., 1995). Similar petrographic characteristics, in particular the presence of pseudoleucite phenocrysts in the volcanic and early phases of the intrusive rocks, have led to the proposal that the Galore Creek Suite is likely coeval with the shoshonitic volcanic rocks (Logan, 2005). Syenitic and monzonitic dikes and stocks are the dominant rocks intruding the volcano-sedimentary package (Figs. 2 and 5). The intrusive sequence, that is pre-, syn-, or post-mineral, was originally defined relative to the formation of the main Cu-Au sulfide event in the Central Zone. Work since 2002 has shown that this sequence does not apply to the district as a whole, and that at least two mineralizing events are present. Nonetheless, the oldest intrusives are pseudoleucite-phyric syenites, followed by early and late-phases of orthoclase and pseudoleucite-phyric syenite, which can contain megacrysts of pseudoleucite and orthoclase. These intrusives commonly have accessory magnetite, apatite, and minor clinopyroxene phenocrysts. Younger syenite intrusions lack pseudoleucite, have distinct tabular orthoclase megacrysts and more abundant clinopyroxene phenocrysts. Plagioclase and biotite phenocrysts may also be present. Equigranular to microporphyritic and sparsely porphyritic equivalents of these units are also encountered. The youngest intrusives in the Galore Creek complex are orthoclase syenites that contain orthoclase megacrysts as well as significant plagioclase, biotite, local hornblende and accessory magnetite and apatite. Orthoclase megacrystic syenite is late to post-mineral to several of the mineralized centers but pre-mineral to others. The youngest phases of intrusive rocks, are post-mineral and include plagioclase-phyric diorites, biotite-phyric lamprophyres, as well as aphanitic mafic, intermediate and felsic dikes.

U-Pb dating of the intrusive complex, done by Mortensen et al. (1995), is limited. A pseudoleucite-orthoclase syenite porphyry that is early mineral, or potentially syn-mineral (see below) returns a U-Pb age on zircon and a titanite-K-feldspar isochron age of 210±1 Ma (Fig. 5). Two orthoclase megacrystic syenite intrusions that are late to post-mineral in some of the mineralized centers and pre-mineral in others return U-Pb zircon age of 205±2.3 Ma and titanite age of 200.1±2.2 on one sample and a titanite-K-feldspar isochron age of 205±1.8

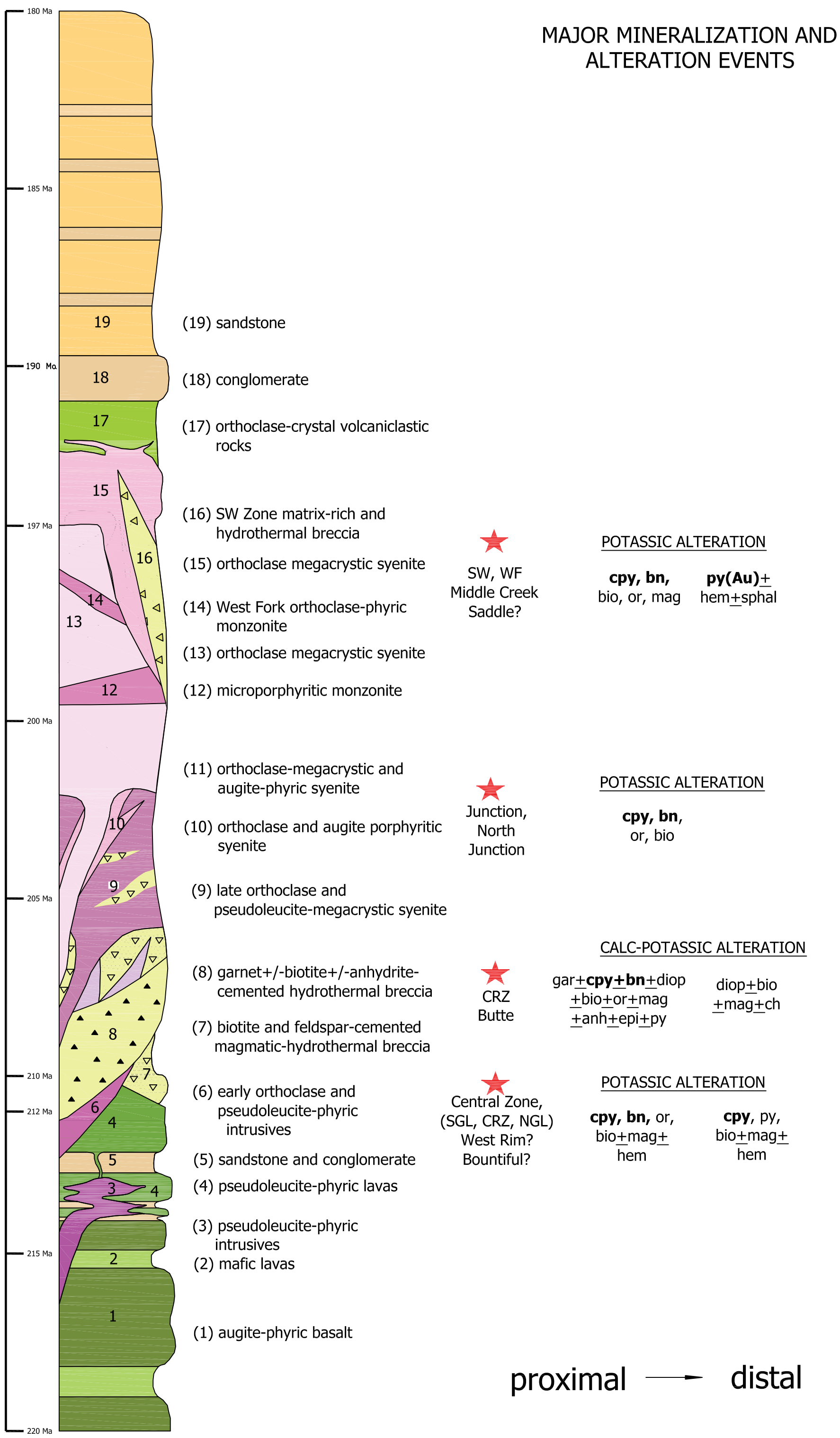

Figure 5. Generalized stratigraphic, intrusive, mineralization and alteration sequence at Galore Creek.

on another body. A younger 197.2±1.2 Ma age derived from a titanite - K-feldspar isochron from a post-mineral dike is interpreted to represent cooling in the Early Jurassic (Mortensen et al., 1995).

Igneous-cemented, hydrothermally cemented, and rock-flour matrix-rich breccias are present at Galore Creek (Enns et al., 1995; Micko et al., 2007) and occur throughout the life of the system (Fig. 5). Igneous-cemented breccias form part of the margins of the Central Zone as a polymict, orthoclase-phyric syenite- cemented breccia and as monomict feldspar-phyric monzodiorite-cemented breccia. Hydrothermally cemented breccias are more voluminous and commonly host significant sulfide minerals. The largest hydrothermal breccia crops out in Dendritic Creek (Fig. 3) where it is a polymict garnet-diopside-biotite cemented breccia. Polymict magnetite-diopside cemented hydrothermal breccia also occurs in the North Gold Lens (NGL), South Gold Lens (SGL) and Southwest Zone (Fig. 2). Monomict to polymict in-situ biotite-chalcopyrite-orthoclase cemented breccia are also known in the Southwest Zone, however, the dominant type here is a polylithic, poorly sorted, rock flour matrix-rich breccia containing pebble to cobble-sized, sub-rounded intrusive clasts.

STRUCTURAL HISTORY

Logan and Koyanagi (1994) recognize up to four deformational events within the Stikine-Iskut River region, three of which pertain to the structures within the Galore Creek valley. The most prominent event affecting Permian and Triassic stratigraphy was the obduction of the Cache Creek Terrane onto the western margin of Stikinia followed by a Jura-Cretaceous deformation forming the Skeena fold belt. The supracrustal rocks at Galore Creek have been interpreted to have undergone early and broad-scale post-Triassic north-south compression followed by post-early Jurassic open to tight folding and related faulting from east-west compression leading to the formation of northerly trending folds and thrust faults (Logan and Koyanagi, 1994).

The most visible structures within the Galore Creek district are the west-dipping Butte Thrust Fault (Figs. 2 and 5) and the east-dipping Copper Canyon Thrust Fault (Fig. 3) (Bottomer and Leary, 1995). Isoclinal folds with a weak, disjunctive pressure solution cleavage parallel to the axial surfaces deform the supracrustal sequences in the hanging wall of the Butte Thrust Fault.

Northwest-trending dextral(?) faults such as the Scud River (Logan and Koyanagi, 1995) and the correlative Friendly Faults (Fig. 6) formed during north-south shortening. East-west contraction is interpreted to have formed a broad south-plunging north-trending anticline in the Galore Creek valley (Fig. 6). Deformation in the hanging wall of the Butte Thrust Fault is also interpreted to be the result of shortening. The Copper Canyon Thrust, which places Permian limestone over the Stuhini Group that hosts the Copper Canyon porphyry Cu deposit also formed during a westerly directed compressional event.

At the deposit scale, easterly trending faults and lineaments, such as the Junction Fault, northwest-trending faults such as the Southwest Fault, and north-trending faults such as the East, Central and West Fork Faults are also recognized (Fig. 6). The West Fork Fault has been documented to have as much as 300 meters of sinistral displacement. The other faults display post-mineral movement of unconfirmed amounts. Faults that were active prior to or during mineralization have yet to be recognized with confidence.

MINERALIZED AND ALTERED ZONES

The known mineralized zones (Figs. 2, 5, and 6) at Galore Creek are hosted in volcanic and volcaniclastic rocks, intrusive rocks, and breccia. The relationship of the mineralized zones to the various intrusive complexes, suggests that there were at least two distinct periods of hydrothermal activity. The earliest period predates intrusion of distinctive orthoclase megacrystic syenite intrusions, whereas later episodes post-date those bodies.

Disseminated and replacement-style mineralization and alteration predominate over vein-dominated styles, which makes the Galore Creek porphyry deposits distinct from those associated with silica saturated alkalic igneous complexes, such as Mount Polley (Sketchley et al., 1995) and Cadia-Ridgeway (Wilson et al., 2003). The Central Zone hosts most of the economic resources, and more is known about it than other deposits on the property (e.g., Enns et al., 1995; Lang et al., 1995a; Micko et al., 2007). Peripheral deposits have been explored to varying extents, and some, such as the Bountiful Zone and the West Fork Zone have only been recently discovered. The following descriptions of the mineralized zones are presented in the order of their relative timing starting with the oldest.

Central Zone

The Central Zone is situated along the eastern margin of the orthoclase megacrystic syenite (Fig. 2). In plan view, there is an elongate north-south zonation from a calc-potassic core in the Central Replacement Zone (CRZ) outward to a more typical K-silicate assemblage in the North Gold Lens (NGL) and South Gold Lens (SGL)(Fig. 6). The calc-potassic assemblage in the core of the CRZ is dominated by hydrothermal garnet ± diopside ± biotite ± orthoclase ± magnetite ± anhydrite ± epidote ± chalcopyrite ± pyrite ± bornite (Figs. 7 and 8). A chalcopyrite-pyrite-orthoclase-biotite assemblage forms the northern and southern margins of the CRZ in transition to the NGL and SGL zones. A K-silicate assemblage of chalcopyrite-bornite-orthoclase-biotite defines the core of the NGL and SGL. The main Cu sulfide in the CRZ is chalcopyrite which has low associated Au values (~0.3 g/t). Higher Au grades (up to 1g/t or greater) are encountered in the core of the NGL and SGL (Figs. 7 and 8), where they are associated with K-silicate alteration as well as chalcopyrite and bornite. Cu:Au ratios in the CRZ are 5:1 whereas in the chalcopyrite-bornite zones of the NGL and SGL are 2:1.

In the NGL, chalcopyrite and bornite are associated with biotite ± orthoclase ± magnetite ± hematite in the volcano-sedimentary package (augite-phyric coherent rocks, pseudoleucite-phyric flows and associated volcaniclastic sedimentary rocks) (Fig.5). Mineralization is somewhat tabular and dips moderately to the west-northwest. A calc-potassic assemblage of garnet-anhydrite-biotite ± chalcopyrite ± pyrite overlaps the K-silicate alteration, but is predominantly situated at depth in the augite-phyric coherent rocks. Micko et al.(2007) describe a polymict hydrothermal breccia near the margin of the late- to post-mineral orthoclase megacrystic syenite complex that is cemented with ± diopside ± magnetite ± garnet ± biotite ± chalcopyrite and ± bornite.

In the CRZ, a calc-potassic alteration assemblage (garnet-biotite-anhydrite ± diopside ± magnetite) predominantly forms the cement to a polylithic breccia containing clasts of orthoclase and pseudoleucite-phyric syenite. It also replaces pseudoleucite-phyric coherent rocks in the CRZ. Where present, chalcopyrite ± bornite occurs as replacement-style mineralization of pseudoleucite-phyric coherent rocks, volcaniclastic sandstone pebble conglomerate, and breccia.

The SGL hosts the youngest mineralizing events (Micko et al., 2007) in the Central Zone. There, Cu and Au are part of an alteration assemblage of orthoclase-biotite ± bornite ± chalcopyrite (Figs. 5 and 8). A calc-potassic alteration assemblage of biotite-magnetite-diopside is also associated with localized chalcopyrite ± bornite. Proffett (2004, 2005) documents a potassic alteration event, based on surface investigations, that includes albite and muscovite in addition to disseminated biotite, chalcopyrite and bornite. Magnetite and hematite are not important alteration products at this stage. The mineralization is hosted by bedded sandstone, orthoclase-rich volcaniclastic sedimentary rocks, early orthoclase and pseudoleucite-phyric syenite and hydrothermal breccia. Lithic fragments and the rock-flour matrix of the hydrothermal breccia are altered to biotite, feldspar, bornite and chalcopyrite. Early pseudoleucite-orthoclase syenite occurs marginal to the breccia and as abundant clasts within the breccia. Proffett (2005) suggests from this spatial association that this intrusion was

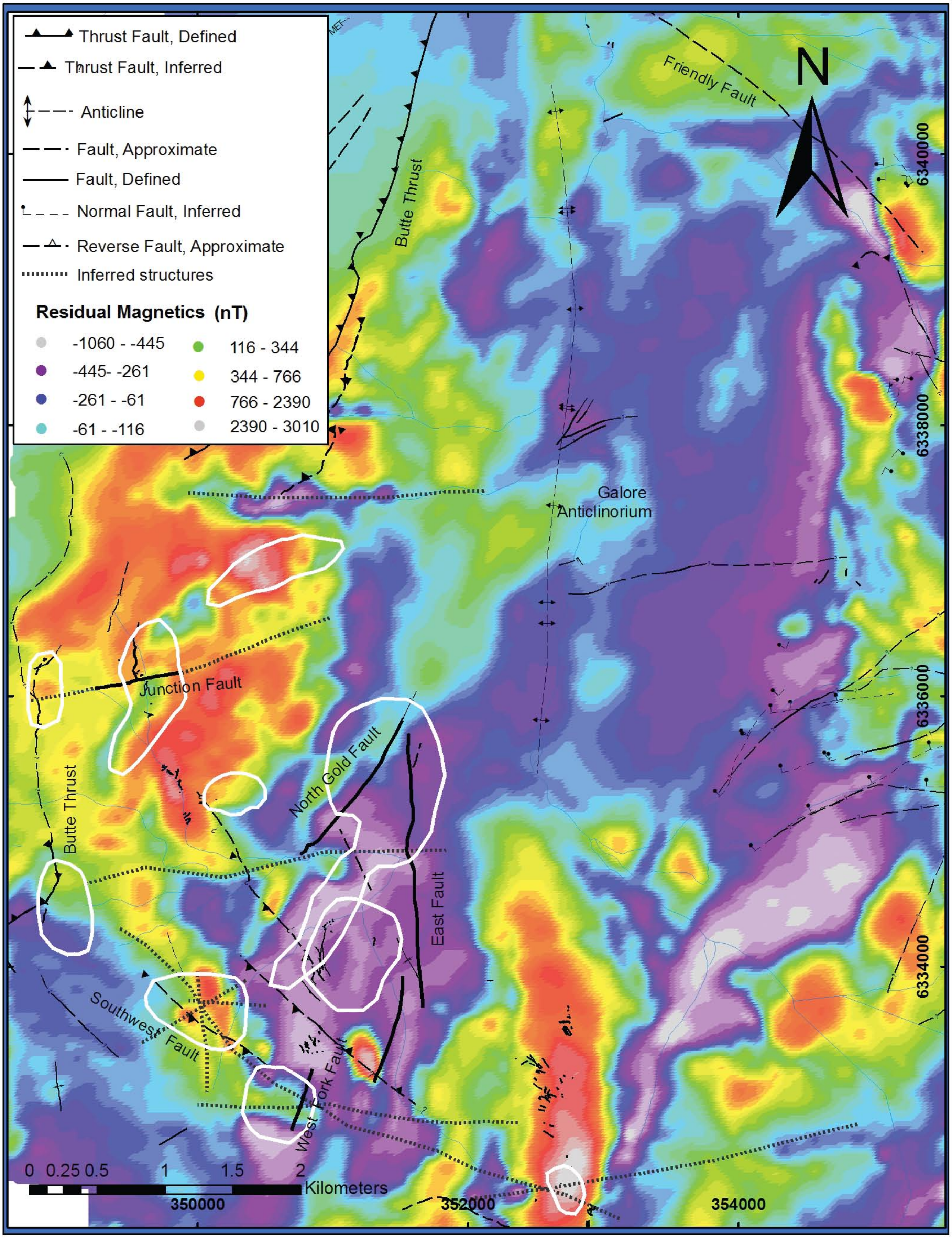

Figure 6. Faults displayed over the residual reduced to pole magnetic map of Galore Creek. Location of mineralized zones as in Figure 2.

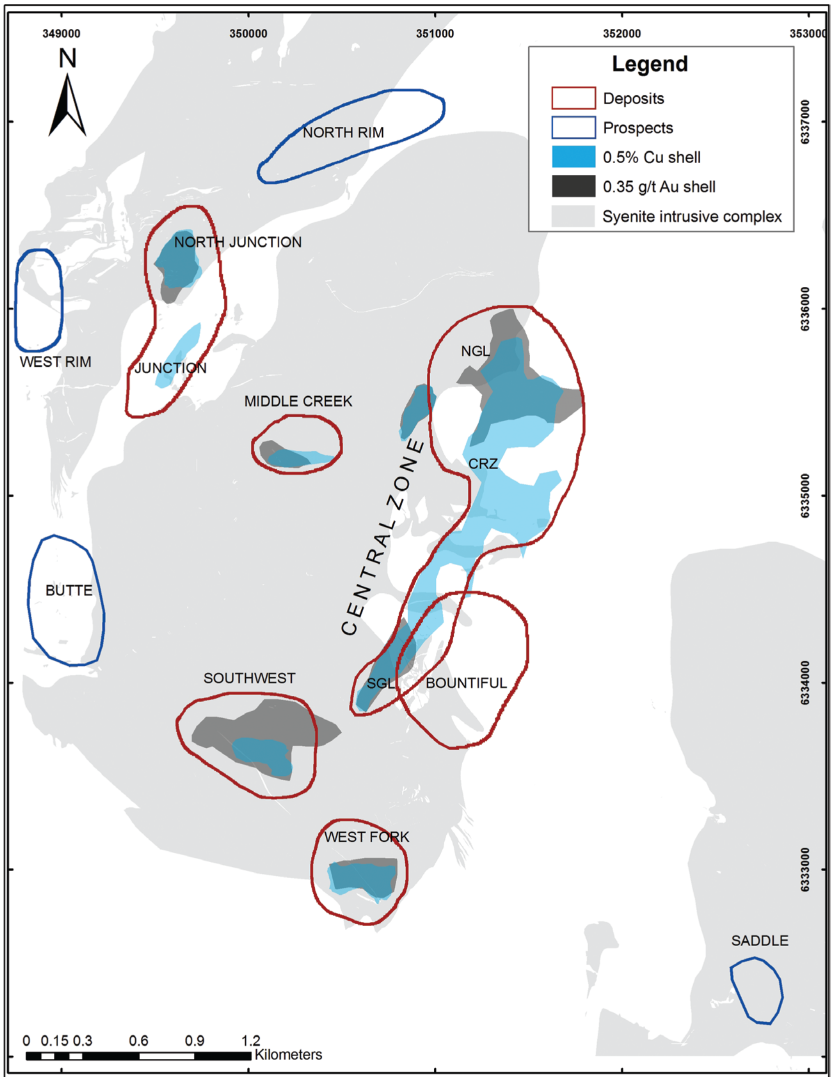

Figure 7. Map of Cu and Au distribution of Galore Creek.

contemporaneous with breccia formation and possibly mineralization. A later orthoclase and pseudoleucite-megacrystic syenite porphyry, the most voluminous intrusive phase in the SGL, may have intruded late in the breccia formation as indicated by similar but less intense alteration than early orthoclase and pseudoleucite-phyric syenite and the breccias.

Sericite-anhydrite-carbonate (SAC) alteration (Fig. 6) overprints the dominant early alteration phases and is locally pervasive and commonly associated with fault zones (Enns et al., 1995). Propylitic alteration, consisting of variable proportions of chlorite, epidote, carbonate, pyrite and hematite forms a halo to the Central Zone (Fig. 8). Selective garnet alteration also occurs with this assemblage in the alkalic intrusive complex. A large pyrite halo about the eastern margin of the deposit is indicated by drilling (Fig. 8).

One of the more distinctive aspects of the Central Zone, in addition to the extensive calc-silicate alteration is the apparent reverse zonation of the Cu-Fe sulfide minerals (Figs. 7 and 8). Bornite dominates the auriferous northern and southern margins of the CRZ, whereas chalcopyrite dominates the core. In most porphyry Cu deposits, the reverse is the case, with the transition from bornite to chalcopyrite reflecting a decrease in temperature (Seedorff et al., 2005). Recently, NovaGold staff demonstrated and Micko et al. (2007) subsequently described in detail that this sulfide zonation is the effect of superimposed mineralization and alteration events with an older bornite-dominated chalcopyrite ± biotite ± orthoclase ± magnetite ± hematite alteration being overprinted by the chalcopyrite-dominated calc-potassic assemblage associated with the formation of the hydrothermal breccia at depth. Spatially, garnet alteration trends north-northeast, dips shallowly to the west and disrupts the north trend of mineralization and potassic alteration within the Central Zone. Petrographic examination of mineralization in the calc-potassic assemblages of the CRZ (Proffett, 2007) indicates an earlier deposited fine-grained bornite associated with coarse-grained chalcopyrite and garnet. A possible interpretation is that the chalcopyrite formed by remobilization of Cu from the fine-grained bornite during introduction of garnet. At least two phases of garnet precipitation post-date the initial chalcopyrite-bornite mineralizing event (Enns et. al., 1995; Micko et al., 2007).

East-west zonation of Cu-Fe sulfides in the NGL and SGL however, display more typical patterns. From west to east, bornite mineralization is enveloped by chalcopyrite mineralization progressing to a predominance of pyrite along the easternmost fringes of the deposit. This zonation is consistent with causative intrusions being sourced from the syenite intrusive complex, as speculated above.

Base-metal concentrations are also zoned in and around the Central Zone Background values for Pb and Zn on the property are usually less than 5 and 20 ppm respectively, whereas Pb and Zn values are elevated within and peripheral to the Cu grade shell. Typical values of Zn concentration are greater than 1000 ppm within the deposit, with Zn concentrations being >500 ppm 100 meters from the zone of strongest Cu-Au mineralization, and Zn >100 ppm about 350 meters from nearest Cu-mineralized zone. Pb may vary from >100 ppm in the ore zone and >15ppm about 350 m from nearest Cu mineralized zone.

Butte Zone

The Butte Zone (Fig. 2) is located on the western margin of the Galore syenite intrusive complex. A chalcopyrite-orthoclase-biotite-garnet ± pyrite assemblage is hosted in pseudoleucite-phyric coherent rocks (Fig. 5). A biotite-chlorite-magnetite-diopside-garnet-epidote-cemented polylithic hydrothermal breccia

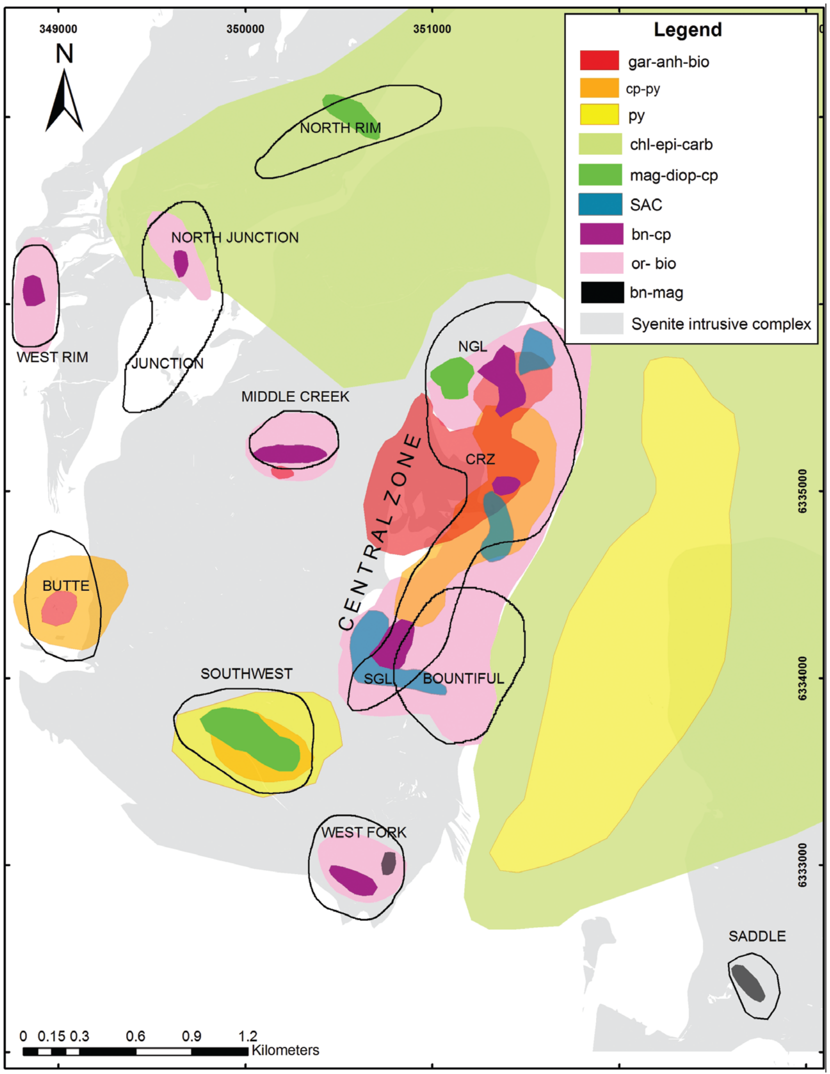

Figure 8. Alteration assemblage map of Galore Creek projected from a depth midway through each deposit (for example, at a 250m depth in the Central Zone). Bn, bornite; Py, pyrite; Or,orthoclase; Bio, biotite; Mag, magnetite; Cp, chalcopyrite; Diop, diopside; Gar, garnet; Anh, anhydrite; SAC, sericite-anhydrite-carbonate; Chl, chlorite; Epi, epidote; and Carb, carbonate

is also known from the limited exploration drilling (Fig. 8). The alteration style, host rocks and elevated Pb and Zn values of the Butte Zone suggest similarities to the CRZ. The Butte Zone is also intruded by late- and post-mineral orthoclase megacrystic syenite.

Bountiful Zone

Discovered beneath the eastern margin of the SGL in 2003 by deep drilling, the Bountiful Zone (Fig. 2) consists of a chalcopyrite-pyrite-biotite-magnetite-orthoclase assemblage (Fig.8) hosted by pseudoleucite-phyric volcaniclastic rocks, overlying siltstone and sandstone, and a hydrothermally cemented polylithic breccia. The pseudoleucite and orthoclase phyric syenite form the intrusive host rocks to a cross-cutting hydrothermally cemented breccia. The syenite also forms the dominant clast type which is locally well mineralized with chalcopyrite. Based on 100m–spaced drilling, a pod-shaped breccia occurs in the zone of best Cu mineralization. Clast size decreases towards the center of the breccia body. A finger of unbrecciated orthoclase and pseudoleucite megacrystic syenite extends eastward from the main syenite stock and terminates within the breccia. The relationship between the unmineralized rock and the breccia is not uniquely constrained, as unequivocal intrusive contact relationships have not been established. Nonetheless, the spatial relationship and the presence of pseudoleucite megacrystic syenite clasts suggest that the latter intrusive may have initiated brecciation and is the candidate causative intrusion for Bountiful Zone mineralization.

Although the Bountiful Zone is located at depth beneath the SGL, it is unclear whether the two mineralized zones are related genetically or whether one event postdates the other. whether one is older or younger. This zone may represent a slightly later event or a lower temperature expression of the chalcopyrite-bornite of the SGL.

North Junction and Junction

The mineralization at North Junction (Fig. 2) is dominated by bornite and chalcopyrite and is associated with orthoclase-biotite-anhydrite alteration (Figs. 7 and 8). Mineralization in this zone is largely magnetite-destructive. Peripheral alteration consists of iron carbonate, garnet and pyrite as well as Na-alteration as indicated by the multi-element ICP-MS data (unpublished data). Host rocks are a suite of orthoclase, augite, biotite, magnetite and apatite phyric syenite. The intrusions and mineralized rocks trend southwest and are northwest dipping. Mineralization is hosted by intrusive rocks that cross-cut the Butte and West Rim Zone. The North Junction and Junction mineralizing event is considered to be younger than the Central Zone mineralization.

West Fork

Disseminated chalcopyrite and bornite of the West Fork Zone and the high-grade Opulent Zone mineralization (>2.5% Cu), with massive magnetite-chalcopyrite-bornite, form two distinct mineralized zones in the West Fork of Galore Creek (Figs. 2 and 8). West Fork Zone mineralization represents the earlier event. It is hosted in multiple intrusive phases including pseudoleucite and orthoclase-phyric syenite and younger monzonite intrusions and volcaniclastic rocks (Fig. 6). The mineralized zone is tabular, strikes west and dips to the north. The host rocks are altered by a K-silicate alteration assemblage of orthoclase, biotite and anhydrite (Fig. 8). The younger Opulent Zone is characterized by a south striking, west-dipping magnetite-chalcopyrite-bornite-anhydrite-cemented hydrothermal breccia. The hydrothermal breccia is hosted within a polylithic igneous cemented breccia containing clasts of pseudoleucite and orthoclase-phyric syenite and orthoclase megacrystic syenite. Both the Opulent Zone and the West Fork Zone mineralization are younger than the Central Zone based on cross-cutting relationships. The West Fork Zone is hosted in-part by a monzonite that intrudes the orthoclase megacrystic syenite that is late- to post-mineral in the Central Zone.

Southwest Zone

The Southwest Zone (Fig. 2) is distinct from Central Zone mineralization in that it is hosted in orthoclase megacrystic syenite that is post-mineral in the Central Zone. (Enns et al., 1995). As a tabular body which trends roughly east and dips moderately to the south, its host rocks consist of a steeply dipping, heterolithic, matrix-dominated breccia in which cement-dominated breccia is present. In situ monolithic cemented breccias formed in the adjoining late orthoclase megacrystic syenite wall rocks.

The most intensely mineralized rock appears to be where this zone intersects the steeply dipping overhanging, northerly trending, contact between the matrix-dominated breccia and the orthoclase megacrystic syenite wall rock (Enns et al., 1995). Hydrothermal minerals consisting of biotite-orthoclase-anhydrite-magnetite altered and locally cemented the breccia, and are closely related to chalcopyrite ± trace bornite and pyrite (Figs. 5, 7, and 8). Sulfide minerals are mostly fine-grained and disseminated within the matrix-dominated breccia. Cement-dominated breccias host blebby infill sulfide in addition to fine-grained disseminated sulfide. In the adjoining wall rocks, sulfide minerals are disseminated and fracture controlled. Monolithic in situ cemented breccia hosts the best grade in the wall rocks. Cu-Au in the Southwest Zone post dates the orthoclase megacrystic syenite intrusions and, by inference, is younger than the Central Zone.

The mineralized core of the Southwest Zone is surrounded by a calc-potassic assemblage consisting of diopside ± biotite ± magnetite (Figs. 6 and 8). Similar alteration assemblages are recognized in the hydrothermal breccias in the NGL, SGL and North Rim areas. A northeast zonation from high Cu-Au to high Au-low Cu is evident in the Southwest Zone (Fig. 7). Disseminated pyrite and less intense alteration and limited Cu-Fe sulfide minerals characterizes the Au-rich but Cu-poor parts of the resource. Sphalerite, galena and native Au are associated with pyrite. Pb and Zn also increase to the northeast.

Other mineralized occurrences

In the Saddle Zone (Fig. 2), a magnetite-epidote-bornite-chalcopyrite assemblage occurs within an east-trending hydrothermal breccia at the contact between late-intrusive monzodiorites (Barr, 1965). Prominent east-trending lineaments and east- trending faults intersect the breccia and may indicate a structural control to the mineralization (Fig. 6). Two major structural trends are identified; steeply-dipping northwest-trending faults and east-trending low angle faults. In the North Rim Zone, magnetite-diopside ± garnet ± chalcopyrite ± bornite occurs in late-mineral monzonite and orthoclase-megacrystic syenite along an apparent northwest trend.

Similar to the Southwest Zone, the Middle Creek prospect is hosted in late-orthoclase megacrystic syenite. It is characterized by disseminated bornite, chalcopyrite and magnetite associated with pervasive fine-grained biotite ± garnet alteration, within a polylithic breccia (Figs. 2, 5, and 8). The breccia has an igneous or hydrothermally altered rock flour matrix and clast types in the breccia include late-mineral orthoclase megacrystic syenite. This indicates that mineralization is later than the Central Zone event. Diopside appears peripheral to the strongest Cu-Fe sulfides and the mineralization has an apparent east trend.

Another prospect, the West Rim, lies to the north of the Butte Zone (Fig. 2). There, chalcopyrite-bornite is associated with a K-silicate assemblage of magnetite-orthoclase-biotite (Fig. 8) hosted by volcanic-sedimentary rocks and conglomerates. Orthoclase megacrystic syenite dikes intrude the mineralized rock. The overall character and the relationship to the orthoclase megacrystic syenite intrusion suggest formation of the West Rim prospect was broadly contemporaneous with the Central Zone.

The Copper Canyon deposit located six kilometers east of the Galore Creek intrusive complex (Fig. 3), has many similarities to the Galore Creek deposits and prospects. Cu-Au mineralization is centred on a magmatic-hydrothermal intrusive breccia (Twelker, 2006). This mineralization is associated with a calc-potassic assemblage consisting of orthoclase-biotite-garnet-hematite-magnetite-chalcopyrite-pyrite-sphalerite. An ankerite-sericite-pyrite ± fluorite ± albite ± anhydrite forms adjacent to the core and is associated with high Au and low Cu mineralization.

FLUID CHEMISTRY

Fluids responsible for alkalic porphyry deposits are characterized by hypersaline brines (>30 eq. wt. % NaCl), high temperatures (300-600°C), low-density vapor, and high oxidation states ($H_2S = SO_4^{2-}$) (Lang et al. 1995a; Wilson et al., 2003, 2007). Fluid inclusions from Galore Creek garnets contain both fluid and vapor, and inclusions with halite contain between 26-60 wt. % NaCl (Dunne et al., 1994; Lang et al., 1995a). In addition, homogenization temperatures for garnet inclusions indicate that calc-potassic alteration formed between 450 and 650°C (Dunne et al., 1994). Chalcopyrite and bornite exsolution textures observed in the Central Zone (Allen, 1966) also indicate high temperatures with a minimum of 475°C. Indications of an oxidized fluid include the ubiquity of hydrothermal magnetite, anhydrite, abundant hematite, and titanite. Sulfide ‰ $\delta^{34}S$ values may evolve to more negative values in oxidized systems and indicate magmatic derivation (Wilson et al., 2002). Sulfide ‰ $\delta^{34}S$ values for Galore range from -3.5‰ to -11‰ in the Central Zone (Deyel et al., 2004, Deyell, 2005) consistent with fluids dominated by an oxidized and magmatic source.

Petrographic examinations of igneous apatite in orthoclase- and pseudoleucite-phyric syenite in the SGL indicate a coexisting gas and fluid phase (Proffett, 2005). The presence of liquid and gas-rich fluid inclusions in apatite together indicate that retrograde boiling occurred. This mechanism results in a rise in vapor pressure, which initiates rapid expansion and brecciation if it exceeds tensile strength and confining pressure of the surrounding rock. In the SGL, Proffett (2005) associates orthoclase and pseudoleucite-phyric syenite with brecciation and proposes it as a possible causative intrusion. Boiling, as indicated by the apatite inclusions, may have been the mechanism responsible for precipitating Au and Cu, although other mechanisms such as cooling and dilution cannot be excluded.

Beyond the Central Zone, Pb and Zn form a halo of anomalous elements in the rocks up to a minimum of 350 meters from the edge of the mineralized centers. These elements are more mobile than Cu with decreasing temperatures, therefore this zonation is expected (Jones, 1992).

SUMMARY AND CONCLUSIONS

Galore Creek was formed in a late Triassic island arc setting during a discrete time prior to the amalgamation of the marine arc with the continental margin. Facies transitions between Copper Canyon and Galore Creek suggest an eruptive center (Copper Canyon) adjacent to a westward deepening basin. Subaqueous volcanism and derivative volcaniclastic rocks were deposited in the apron around the arc edifice. Syenitic and monzonitic sills, stocks and dikes intruded the volcanic sequence, and are associated with porphyry Cu-Au centers. Mineralized clusters formed on the margin of and within a large syenite intrusive complex.

A key observation is that there were at least two major mineralizing events with differing apparent orientations. A generalization with regards to mineralization trends and timing among the mineralized zones appears to indicate a common northerly orientation for older and volumetrically more significant mineralizing events (SGL, NGL, Butte, West Rim and Bountiful) that may reflect the permeability structure which controlled intrusion and hydrothermal circulation at this time. Earliest Cu-Au deposition was apparently tied primarily to intrusive events, so structures may have only provided a secondary influence by localizing intrusions. Younger mineralized centers (Southwest Zone, West Fork Zone, Middle Creek) that post-date the orthoclase megacrystic syenite are dominated by easterly and westerly trending orientations. Moreover, the intersection of easterly trending permeability structures with older structural fabrics seems to have localized still other mineralized zones (Saddle Zone, North Rim?). Northwest-trending fabrics, including lineaments visible in aeromagnetic data that connect Saddle Zone, West Fork and Southwest Zone, may have localized mineralization along this trend (Fig. 6). A prominent east-west lineament visible in aeromagnetics (Fig. 6) corresponds with the long axis of the garnet-cemented Dendritic Creek hydrothermal breccia and may have controlled this later garnet alteration and mineralization event (Enns et al.. 1995). The lineament can be projected to the Butte Zone, and may explain the similarities in alteration style at Butte.

Fluids responsible for mineral assemblages in the Central Zone were saline, oxidized and magmatic in origin, consistent with observations of fluid chemistry from other oxidized porphyry Cu deposits. Localized brecciation associated with hydrothermal activity in conjunction with fluid inclusion observations suggest that secondary boiling may have contributed to Cu and Au deposition at Galore Creek. In contrast, cooling may be a more plausible explanation to explain pervasive replacement and disseminated alteration styles.

The alteration and mineralization history at Galore Creek is complex with multiple intrusive, hydrothermal and mineralizing events characterizing the deposit. The earliest events affected the volcanic and sedimentary rocks and early intrusions (Central Zone, Butte, West Rim) and the latest events post-dated the orthoclase megacrystic syenite (Southwest, Opulent, Middle Creek, Saddle, North Rim) (Fig. 5). Mineralizing events intermediate in the timing sequence may be represented by the North Junction, Junction and West Fork Zones. There is still much about the deposits and their geologic setting that is poorly understood. In particular, more work is needed to complete our understanding of the igneous and hydrothermal genesis of the deposit, mechanisms of ore deposition, the nature of structural controls and the tectonic factors that influenced the formation of this metallogenic event.

ACKNOWLEDGMENTS

This manuscript is summarized from a considerable body of work completed by the various exploration companies at Galore Creek, including NovaGold Resources, Stikine Copper, Kennecott Canada, and Hudson Bay Mining and Smelting (now Anglo American Exploration Canada).

Special thanks are owed to MDRU graduate students Janina Micko and Kevin Byrne for valuable geologic discussions and their tireless commitment to unraveling the mysteries of the Galore Creek deposits. In addition, valuable contributions to our geologic understanding of Galore Creek have been provided by NovaGold geologist Scott Close as well as the many geologists that have faithfully documented the geology observed in drill core. Joe Piekenbrock is owed thanks for continually inciting discussions regarding the genesis of the Galore Creek porphyry system. We are grateful to Rick Van Nieuwenhuyse for encouraging us to write this paper. Valuable advice as to the direction of this paper from Claire Chamberlain is also greatly appreciated.

REFERENCES CITED

Allen, D.G., 1966, Mineralogy of Stikine Copper's Galore Creek deposits: Vancouver, Canada, University of British Columbia, M.S. thesis, 40 p.

Allen, D.G., Panteleyev, A. and Armstrong, A.T., 1976, Porphyry copper deposits of the alkalic suite: Galore Creek, *in* Sutherland Brown, A., ed., Porphyry deposits of the Canadian Cordillera: Canadian Institute of Mining and Metallurgy, Special Volume 15, p. 402-414.

Barr, D.A., 1965, The Galore Creek copper deposits: Canadian Institute of Mining and Metallurgy Bulletin, v. 59, p. 841-853.

Barr, D.A., Fox, P.E., Northcote, K.E. and Preto, V.A., 1976, The alkaline suite porphyry deposits: A summary, *in* Sutherland Brown, A., ed., Porphyry deposits of the Canadian Cordillera: Canadian Institute of Mining and Metallurgy, Special Volume 15, p. 359–367.

Bottomer, L.R., and Leary, G.M., 1995, Copper Canyon porphyry copper-gold deposit, Galore Creek area, northwestern British Columbia, *in* Schroeter, T.,ed., Porphyry copper deposits of the northern Cordillera: Canadian Institute of Mining and Metallurgy, special volume 46, paper n. 46, p. 645-649.

Burnham, C.W., and Ohmoto, H., 1980, Late-stage processes of felsic magmatism: Mining Geology Special Issue 8, p. 1-11.

Cooke, D.R., Wilson, A.J., House, M.J., Wolfe, R.C., Walshe, J.L., Lickfold, V., and Crawford, A.J., 2007, Alkalic porphyry Au-Cu and associated mineral deposits of the Ordovician to Early Silurian Macquarie arc, NSW: Australian Journal of Earth Sciences, v. 54, p. 445-463.

Deyell, C.L., 2005, Sulfur isotope zonation at the Mt. Polley alkalic porphyry Cu-Au deposit, British Columbia (Canada): Proceedings of the 8th biennial meeting of the Society for Geology Applied to Mineral Deposits, p. 373-376.

Deyell, C.L. and Tosdal, R.M. 2005, Alkalic Cu-Au deposits of British Columbia: Sulfur isotope zonation as a guide to mineral exploration: British Columbia Ministry of Energy, Mines, and Petroleum Resources, Paper 2005-1, p. 191-208.

Dunne, K.P.E., Lang, J.R., and Thompson, J.F.H. 1994, Fluid inclusion studies of zoned hydrothermal garnet at the Galore Creek Cu-Au porphyry deposit, northwestern British Columbia: Geological Association of Canada - Mineralogical Association of Canada, Annual Meeting, Waterloo, Ontario, May 1994, Program with Abstracts v. 19, p. A-31.

Enns, S.G., Thompson, J.F.H., Stanley, C.R. and Yarrow, E.W., 1995, The Galore Creek porphyry copper-gold deposits, northwestern British Columbia, *in* Schroeter, T., ed., Porphyry copper deposits of the northern Cordillera: Canadian Institute of Mining and Metallurgy special volume 46, Paper n. 46, p. 630-644.

Gammons, C.H., and Williams-Jones, A.E., 1997, Chemical mobility of gold in the porphyry-epithermal environment: Economic Geology, v. 92, p. 45-59.

Hemley, J.J., Cygan, G.L., Fein, J.B., Robinson, G.R., and d'Angelo, W.M., 1992, Hydrothermal ore-forming processes in the light of studies in rock-buffered systems: 1. Iron-copper-zinc-lead sulfide solubility relations: Economic Geology, v. 87, p. 1-22.

Holliday, J.R., and Cooke, D.R., 2007, Advances in geological models and exploration methods for copper±gold porphyry deposits; Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, p. 791-809.

Jago, P., Tosdal, R., Chamberlain, C., 2007, Mt. Milligan – an exemplary Cu-Au alkalic porphyry system: Arizona Geological Society, Ores and Orogenesis Symposium Program with Abstracts, p. 166-167.

Jones, B.K, 1992, Application of metal zoning to gold exploration in porphyry copper systems: Journal of Geochemical Exploration, v. 43, p. 127-155.

Lang, J.R., 1994, Major and trace element compositional zoning in hydrothermal and igneous garnets from alkalic intrusive complexes in British Columbia: Geological Society of America Abstracts with Programs, v. 26, p. A-369.

Lang, J.R., Stanley, C.R. and Thompson, J.F.H., 1995a, Porphyry copper deposits related to alkalic igneous rocks in the Triassic-Jurassic arc terranes of British Columbia: Arizona Geological Society Digest 20, p. 219-236.

Lang, J.R., Lueck, B., Mortensen, J.K., Russell, J.K., Stanley, C.R. and Thompson, J.F.H., 1995b, Triassic-Jurassic silica-undersaturated and silica-saturated alkalic intrusions in the Cordillera of British Columbia: Implications for arc magmatism: Geology, v. 23, p. 451-454.

Lang, J.R., Thompson, J.F.H., Stanley, C.R., 1995c, Na-K-Ca magmatic hydrothermal alteration associated with alkalic porphyry Cu-Au deposits, British Columbia, *in* Thompson, J.F.H., ed., Magmas, fluids and ore deposits, MAC short course v. 23, Victoria, British Columbia, May 1995, p. 339-366.

Lickfold, V., Cooke, D.R., Smith, S.G., and Ullrich, T.D., 2003, Endeavor copper-gold porphyry deposits, North Parkes, New South Wales: Intrusive history and fluid evolution: Economic Geology, v. 98, p. 1607-1636.

Logan, J.M., 2004, Alkaline magmatism and porphyry Cu-Au deposits at Galore Creek, northwestern British Columbia: BC Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork 2004, Paper 2005-1.

Logan, J.M. and Koyanagi, V.M., 1994, Geology and mineral deposits of the Galore Creek area, northwestern British Columbia (104G/3 and 4): BC Ministry of Energy, Mines and Petroleum Resources, Bulletin 92, 96 p.

Micko, J., Tosdal, R.M., Chamberlain, C.M., Simpson, K, Schwab, D., 2007, Distribution of alteration and sulfide mineralization in the Central Zone of Galore Creek, northwestern British Columiba: Arizona Geological Society meeting, Ores and Orogenesis, Program with Abstracts, p. 175

Mihalynuk, M.G., Nelson, J., Diakow, L.J., 1994, Cache Creek terrane entrapment: Oroclinal paradox within the Canadian Cordillera: Tectonics, v. 13, p. 575-595.

Mihalynuk, M.G., Erdmer, P., Ghent, E.D., Cordey, F., Archibald, D.A., Friedman, R.M., and Johnnson, G.G., 2004, Coherent French Range blueschist: Subduction to exhumation in <2.5 m.y?: Geological Society of America Bulletin, v. 116, p. 910-922.

Monger, J.M., 1977, Upper Paleozoic rocks of the western Cordillera and their bearing on the Cordilleran evolution: Canadian Journal of Earth Sciences, v. 14, p. 1832-1859.

Mortensen, J.K., Ghosh, D. and Ferri, F., 1995, U-Pb age constraints of intrusive rocks associated with copper-gold porphyry deposits, *in* Schroeter, T., ed., Porphyry copper deposits of the northern Cordillera: Canadian Institute of Mining and Metallurgy Special Volume 46, Paper n. 46, p. 142-158.

Nelson, J.L., and Mihalynuk, M. 1993, Cache Creek ocean: Closure or enclosure: Geology, v. 21, p. 173–176.

Otto, B.R., 2004, 2004 geologic and diamond drilling report on the Copper Canyon property: unpublished company report, NovaGold Resources Inc., 43 p.

Otto, B.R., 2006, Tectono-stratigraphic setting of the Galore Creek Cu-Au alkaline porphyry deposits, British Columbia: Canadian Institute of Mining Conference and Exhibition, Program with Abstracts.

Panteleyev, A., 1976, Galore Creek map area, *in* Geological field work, 1975: British Columbia Mininstry of Energy, Mines and Petroleum Resources Paper 1976-1, p. 79-81

Plafker, G. and Berg, H.C., 1994, Overview of the geology and tectonic evolution of Alaska, *in* The Geology of North America Vol. G-1, The geology of Alaska: The Geologic Society of America, p. 989-1021.

Proffett, J.M., 2004 Results of geologic mapping at Galore Creek, British Columbia: unpublished company report, NovaGold Resources Inc., 17 p.

Proffett, J.M., 2005 Progress report on the geology of the southern part of the Main (Central) Zone at Galore Creek, British Columbia: unpublished company report, NovaGold Resources Inc., 43 p.

Proffett, J.M., 2007, Report on the geology of the Main (Central) Zone south of Dendritic Creek, Galore Creek porphyry Cu-Au deposit, British Columbia: unpublished company report, NovaGold Resources Inc., 14 p.

Russell, J.K, Dipple, G.M., Lang, J.R., and Lueck, B., 1999, Major element discrimination of titanian andradite from magmatic and hydrothermal environments: An example from the Canadian Cordillera: European Journal of Mineralogy, v. 11, p. 919-935.

Schroeter, T., Pardy, J., and Cathro, M., 2004, Significant British Columbia porphyry Cu-Au resources: Min. En. Mines, Geo-file 2004-11, 7 p.

Sketchley, D.A., Rebagliati, C.M., and DeLong, C. 1995, Geology, alteration, and zoning patterns of the Mt. Milligan copper-gold deposits, *in* Schroeter, T., ed., Porphyry copper deposits of the northern Cordillera: Canadian Institute of Mining and Metallurgy Special Volume 46, Paper n. 46, p. 650-665.

Seedorff, E., Dilles, J.H., Proffett, J.M., Einaudi, M.T., Zurcher, L., Stavast, W.J.A., Barton, M.D., and Johnson, D.A., 2005, Porphyry-related deposits: Characteristics and origin of hypogene features, *in* 100th Anniversary Volume: Society of Economic Geologists, p. 251-298.

Streck, M.J., and Dilles, J.H., 1998, Sulfur content of oxidized arc magmas as recorded in apatite from a porphyry copper batholith: Geology, v. 26, p. 523-526

Travers, W.B., 1978, Overturned Nicola and Ashcroft strata and their relation to the Cache Creek Group, southwestern Intermontane Belt, British Columbia: Canadian Journal of Earth Sciences, v. 15, p. 99-116.

Twelker, E., 2007, A breccia-centered ore and alteration model for the Copper Canyon alkalic Cu-Au porphyry deposit, British Columbia: Fairbanks, University of Alaska, M.S. thesis, 141 p.

Wernicke, B., and Klepacki, D.W. 1988, Escape hypothesis for the Stikine block: Geology, v. 16, p. 461–464.

Wilson, A., Cooke, D.R., Thompson, J.F.H., 2002, Alkalic and high-K calc-alkalic porphyry Au-Cu deposits: A summary, *in* Cooke, D.R. and Pongratz, J. eds., Giant Ore Deposits: Characteristics, genesis and exploration: CODES Special Publication 4, p. 51-55

Wilson, A., Cooke, D.R., and Harper, B.L. 2003, The Ridgeway gold-copper deposit: a high-grade alkalic porphyry deposit in the Lachlan Fold Belt, NSW, Australia: Economic Geology, v. 98, p. 1637-1656

Wilson, A.J., Cooke, D.R., Harper, B.J., and Deyell, C.L., 2007, Sulfur isotopic zonation in the Cadia district, southeastern Australia: Exploration significance and implications for the genesis of alkalic porphyry gold-copper deposits: Mineralium Deposita, v. 42, p. 465-488.